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Flow Measurement Methods Applied to Hydro Power Plants

Gustavo Urquiza¹, Miguel A. Basurto¹, Laura Castro¹,
Adam Adamkowski² and Waldemar Janicki²

¹*Research Center on Engineering and Applied Science (CIICAp)
from the Autonomous University of Morelos State (UAEM), Morelos*

²*The Szezwalski Institute of Fluid-Flow Machinery,
Polish Academy of Science, Gdansk*

¹*México*

²*Poland*

1. Introduction

Efficiency and maximal power output are two of the most important goals to analyze in hydraulic turbines. Turbines normally operate in variable head conditions; therefore, tests to analyze performance are frequently realized for a selected number of power plant heads. Usually it is limited to three heads: low, medium and high. The efficiency of water turbines is most frequently expressed using the weighted average efficiency or arithmetic mean efficiency, calculated from the measured results in the examined heads. To perform the calculation of efficiency is necessary to know several parameters such as kinetic and potential energy of water due to the position, because of this is required to know the flow rate entering the turbine. The flow rate of water through the turbine (Q) is determined by the volume of water flowing in time unit. The measurement of this quantity is one of most difficult tasks in water turbine tests. Three basic methods of flow rate measurement and results of them will be presented in this chapter.

2. Pressure-time method (Gibson)

One of the basic methods for flow rate measurement applied in hydropower plants is pressure-time method, commonly called the Gibson method. It consists in flow rate measurement by integration of pressure difference between two pipeline cross-sections during fast shut-off. Selected experiences in developing and utilizing the method are presented in this section, which covers cases of flow rate measurements in pipelines of more complex geometry, e.g. curved penstocks. The calculation procedure that provides the possibility to analyze the influence of measurement system components (pressure difference transducer, length and diameter of tubes connecting the pressure taps with a transducer) on measured flow rate has been already developed as the main element of this methodology. Furthermore, utilizing the Gibson method to flow rate measurement through water turbines requires know the leakage rate flow through closed guide vanes, i.e. through the blade

interspaces. The procedure for estimating this rate is presented in this section. Practical application of Gibson method requires preparation of special measurement devices, often installed inside the large-size penstocks and with no possibility to approach the pipeline from the outside. During years 03-09 this method was successfully applied for efficiency tests of units that were carried out at many hydropower plants in Poland and Mexico by the authors of this chapter.

2.1 Theory

This method is based on the water hammer phenomenon taking place in a closed pipe. It was introduced by Norman Gibson (1923), who used the work conducted by Jukowsky in 1898 concerning the water-hammer theory. Gibson's method measures a static pressure difference, between two cross-sections of the penstock as result of momentum variation caused by a quick closing of the wicket gates of the turbine. The flow rate is then obtained by integration, within a proper time interval. Gibson method is recommended by the international standard IEC 41:1991 as well as its European equivalent EN 60041. In the measurement conditions recommended by the standard, the accuracy of the measurement is better than ± 1.5 to 2.3% and it does not stay away from the accuracy of other basic methods for flow measurement. There are three principal versions of the Gibson method:

- i. Direct measurement of the pressure difference between two hydrometric sections of the penstock by means of a transducer of pressure difference, whereas the measuring penstock segment between the sections is straight and has a constant diameter – this version could be called the classical.
- ii. Separate measurement of pressure variations in two hydrometric sections of the penstock is used – version with separate measurement sections.
- iii. Pressure change measurement in one hydrometric section of the penstock and referring these changes to the constant pressure in an open reservoir of the liquid to which the penstock is directly connected – version with single penstock measurement section.

To derive a relationship that calculates the volumetric flow rate Q must be considered a closed pipe with a flow section area A which may change along its length.

Scheme of measuring section on turbine penstock is shown in Figure. 1. Next has to be considered that the water flow must be stopped. Taking into account one segment of length L , limited between sections 1-1 and 2-2 has to be assumed that the velocity and pressure distributions in those sections are constant. Also it is assumed and that the fluid density and the flow section area do not change with water hammer effect.

With these assumptions done, the relation between the parameters of the one-dimension unsteady flow between two selected sections of the pipe can be described using energy balance equation:

$$\alpha_1 \frac{\rho Q^2}{2A_1^2} + p_1 + \rho g z_1 = \alpha_2 \frac{\rho Q^2}{2A_2^2} + p_2 + \rho g z_2 + \Delta P_f + \rho \int_0^L \left(\frac{dQ}{dt} \right) \frac{dx}{A(x)} \quad (1)$$

Where ρ is water density, p_1 and p_2 are static pressures in sections 1-1 and 2-2 of the pipe, respectively (see Fig. 1), z_1 and z_2 are hydrometric levels of sections 1-1 and 2-2, α_1 , α_2 are

Coriolis coefficient (kinetic energy correction coefficient) for sections 1-1 and 2-2, respectively, and finally, ΔP_f is the pressure drop caused by friction losses between sections 1-1 and 2-2. The fourth term on the right-hand side of the above equation represents the hydraulic friction losses in the pipe segment. In the Gibson method, the pressure drop caused by friction is determined from a square flow rate function, written as:

$$\Delta P_f(t) = K_f Q(t) |Q(t)|,$$

Where K_f = constant.

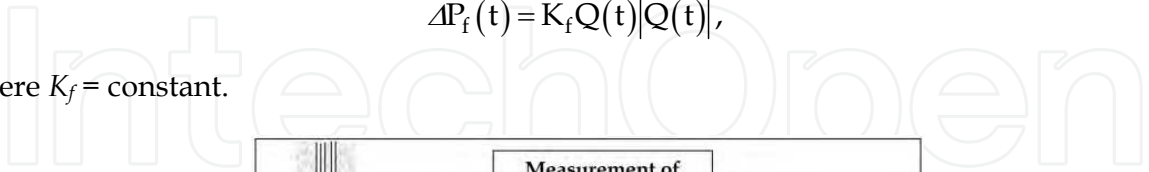


Fig. 1. Penstock and measuring sections in Gibson’s method.

The term at final of equation (1) is the unsteady term, which takes into account the time-history of change of the volumetric flow rate $Q=VA$, recorded during the time period of the water hammer effect. This term represents the effect of fluid inertia in the examined conduit segment. To clarify these considerations some quantities are presented to group terms of equation (1):

- static pressure difference between measuring sections 2-2 and 1-1 related to a reference level:

$$\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1 \tag{2}$$

- dynamic pressure difference between conduit sections 2-2 and 1-1:

$$\Delta p_d = \alpha_2 \frac{\rho Q^2}{2A_2^2} - \alpha_1 \frac{\rho Q^2}{2A_1^2} \tag{3}$$

- geometrical modulus of the penstock segment of a length L:

$$C = \int_0^L \frac{dx}{A(x)} \tag{4}$$

Then we arrive at the differential equation in the form:

$$\rho C \frac{dQ}{dt} = -\Delta p - \Delta p_d - \Delta P_f \tag{5}$$

After integrating equation (5) for the time interval (t_0, t_k) , in which the flow changes from initial to final conditions, was obtained the flow rate difference between those conditions. Then it is assumed that flow rate at final condition (Q_k) is known, i.e. after the cut-off device has been closed, allowing the following expression to be applied for the computation of the volumetric flow rate at initial condition (before starting the water flow cut-off):

$$Q_0 = \frac{1}{\rho C} \int_{t_0}^{t_k} [\Delta p(t) + \Delta p_d(t) + \Delta p_f(t)] dt + Q_k \quad (6)$$

The water flow rate at final condition is different from zero due for instance to water leaks through the closing device, so this will be called leakage flow Q_k and its determined by the empirical equation:

$$Q_k = \mu A_s \sqrt{\frac{2\Delta p_k}{\rho}} \quad (7)$$

2.2 Instrumentation

In order to obtain high accuracy of the measurement, proper selection of the measuring device range is very important. This should correspond well at measured pressure. High-class pressure transducers of various types are nowadays widely available on the market. These are electro-mechanical devices, in which the mechanical effect caused by the pressure is converted to an electric signal. Their advantages include:

- Easy connection at electronic system of measurement data acquisition,
- Negligible flow of liquid through a manometer connector, which secures fast and precise reaction to pressure changes,
- Easy determination of average values of the fluctuating pressure using the data acquisition system,
- Easy recording of the time-history of rapid pressure changes in steady-state and transient conditions using available electronic equipment.

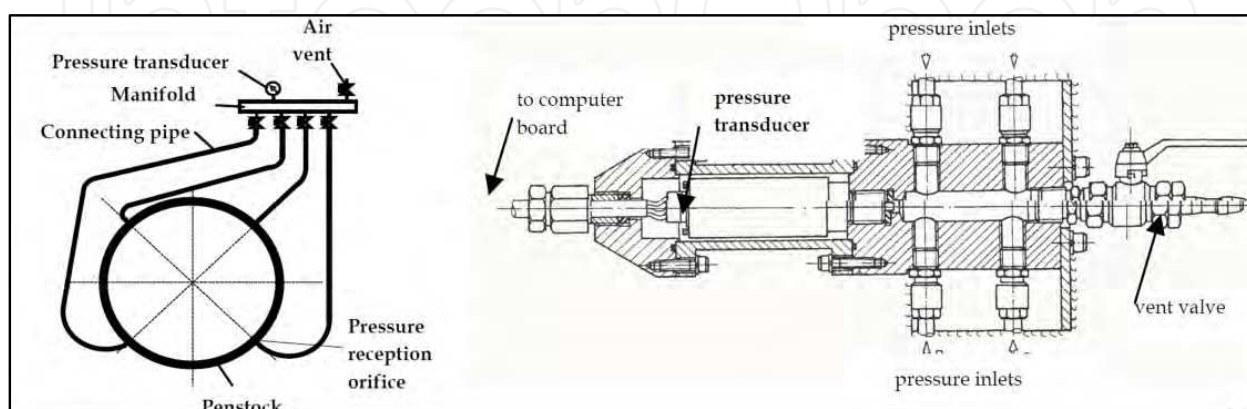


Fig. 2. Scheme of sensing points on penstock and waterproof manifold installed.

2.3 Example

To exemplify the results obtained by this method, some graphics of results are showed. Mainly the graphics of pressure difference vs. time, and efficiency curve calculated vs. mechanical power (figs. 3-5, Castro L. (2011))

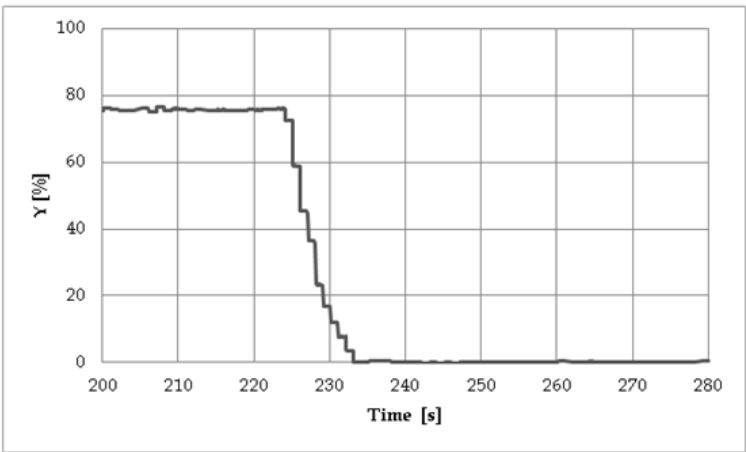


Fig. 3. Differential pressure measured vs. time during closing of the wicked gate

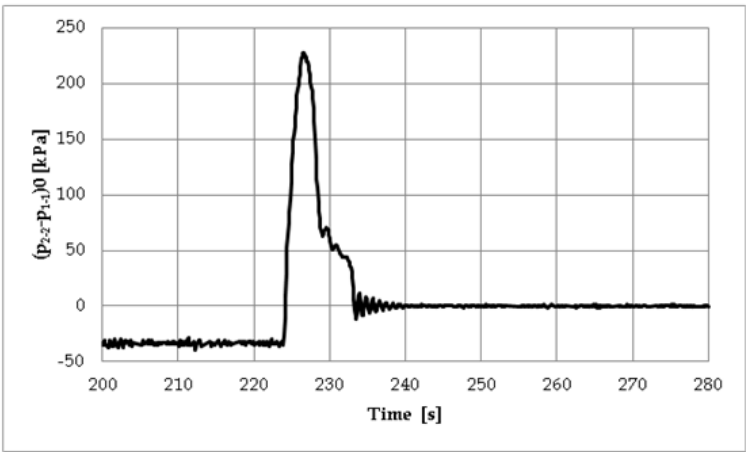


Fig. 4. Pressure difference vs. time during closing of the wicked gate

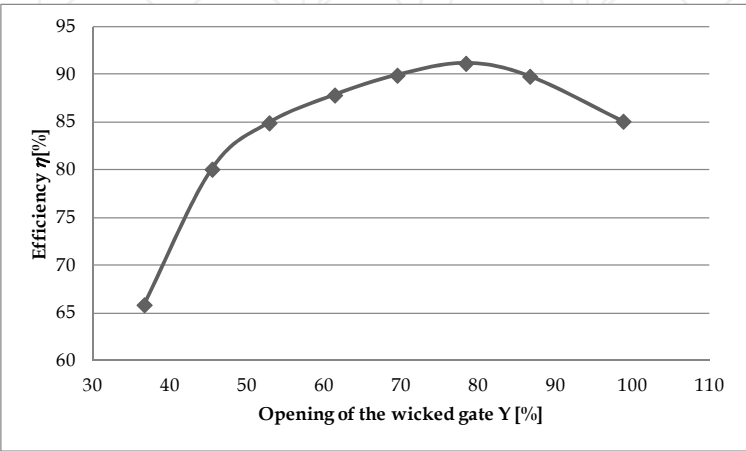


Fig. 5. Efficiency calculated vs. closure percentage of the wicked gate

In table no.1 are showed some or the results obtained in measurements, were the $Q_{turbine}$ is the total volumetric flow, obtained from the addition of Q_{gib} , Q_k and $Q_{cooling}$, the last one, is the flow of water used for cooling air from the electric generator.

Test Number	Opening of the wicket gate Y [%]	Mechanical Power P_{mech} [MW]	Gibson Flow Rate Q_{Gibson} [m ³ /s]	Leakage Flow Q_k [m ³ /s]	Cooling Flow $Q_{cooling}$ [m ³ /s]	Total Flow $Q_{turbine}$ [m ³ /s]	Net Head H_n [m]	Efficiency η_t [%]
1	98.8	31.65	88.97	0.7	0.0	89.67	42.40	85.10
2	86.7	30.71	81.30	0.7	0.0	82.00	42.64	89.80
3	78.4	29.03	75.44	0.7	0.0	76.14	42.75	91.16
4	69.5	26.05	68.03	0.7	0.0	68.73	43.09	89.91
5	61.4	22.63	60.29	0.7	0.0	60.99	43.18	87.84
6	52.9	19.02	52.20	0.7	0.0	52.90	43.27	84.92
7	45.5	15.72	45.41	0.7	0.0	46.11	43.52	80.08
8	36.7	10.14	34.98	0.7	0.0	35.68	44.10	65.89

Table 1. Results from the measurements by Gibson’s method.

In the examined case, the efficiency measurements performed for one hydropower station head with the aid of the Gibson method, were used for determining the efficiency curve of the turbine and the hydro-unit, and for calibrating the measuring system based on the Winter-Kennedy method. Once calibrated, the Winter-Kennedy system can be used for continuous flow rate measurement and for determining turbine performance (efficiency) characteristics of for other power plant heads.

3. Winter Kennedy method

Winter-Kennedy method utilizes the phenomena of a static pressure difference between the outside and the inside of the turbine spiral due to the centrifugal force acting on the curved streams of liquid in the spiral case. Contrary to the Gibson method, this is an index (relative) method, which can be used in water machines efficiency tests only after the calibrating by means of the absolute method.

3.1 Theory

The flow measurement performed with the aid of this method makes use of the following relation between the flow rate Q and the difference of the above named pressures $\Delta p = p_1 - p_2$:

$$Q = K \cdot \Delta p_n \tag{8}$$

Where K is a constant coefficient and n is the power exponent, theoretically equal to 0.5. The values of the constants K and n are determined experimentally during calibration. The results of flow rate measurement performed, using the Gibson method, were used for calibrating the Winter-Kennedy measuring systems installed in the spiral case of one turbine. The pressure difference between two points established in the spiral case of the examined turbine was measured using a high-precision class pressure difference transducer of the accuracy of 0.08%. The Winter-Kennedy method is only used for water turbines or pump-turbines working in turbine mode. It cannot be used for testing pumps due to excessive turbulent flow in the spiral case in pumping conditions.

3.2 Instrumentation

In installations with steel turbine spiral cases, the pressure reception points are located, as a rule, at the same radial section of the case (Figure 6) The outer hole is located on the outer side of the spiral case, while the inner hole outside of the supporting blades, on the streamline going through the centre of their interblade passage. In case of horizontal spiral case it is recommended to distribute the holes in the upper half, providing better conditions for washing (IEC 41: 1991). The pressure reception points should not be located close to welded joints or areas of rapid change of spiral cross section. For the measurement of pressure with this method, was used differential pressure transducer 3051 type CD, range of 0-120 kPa, cl. 0.06, and 0.1 s time constant (Adamkowski 2006).

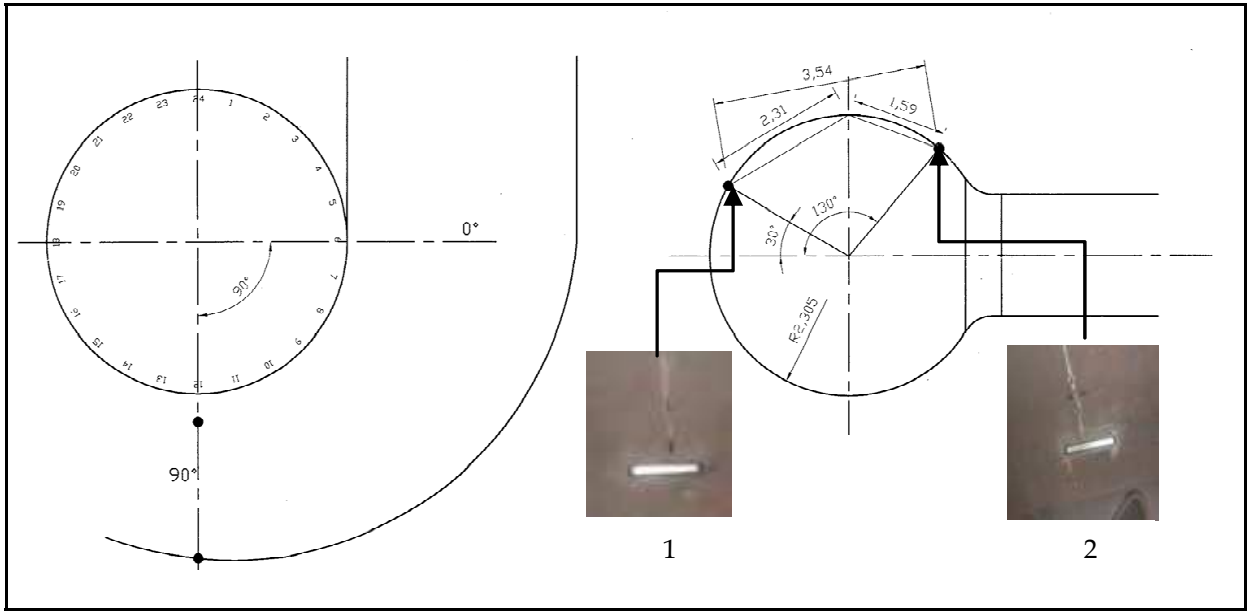


Fig. 6. Localization of the measurement points inside the spiral case (point 1 and 2)

In figure 7 can be observed an example from the location of differential pressure transmitters to measure pressure, outside the spiral case.



Fig. 7. Position of pressure transmitters outside of the spiral case.

3.3 Examples

From the measurements realized by means of Gibson’s method in a turbine in Mexico, was calibrated the Winter-Kennedy system, obtaining the coefficient K, Figure 8 shows the results, a) shows the determination of the coefficient K, which in this case corresponds to a value of 29.42. Also in figure 8 incise b) shows the mean feature of the flow depending on the pressure difference measurements, for pressure taps plate type.

It is remarkable that once calibrated, the Winter-Kennedy system can be used for continuous flow rate measurement and for determining turbine performance (efficiency) characteristics of for other heads.

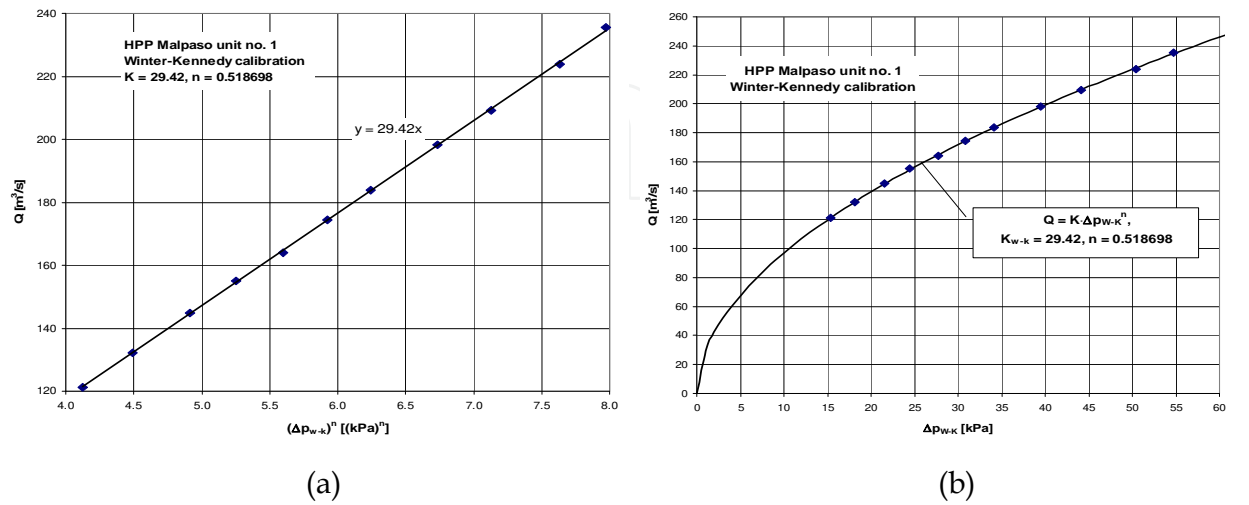


Fig. 8. System features for Winter-Kennedy measurements: (a) determination of K = 29.42 and (b) flow vs differential pressure.

4. Ultrasonic method

This method has been considered in this work solely for the purpose of comparing, but it is noteworthy that the experience concerning the application of the acoustic methods for flow measurements is still limited.

4.1 Theory

The principle of flow measurement using ultrasonic is that the speed of propagation of an ultrasonic acoustic pulse is affected by flow velocity. Accordingly, an ultrasonic acoustic pulse sent upstream travels at a ground speed less than an acoustic signal sent downstream. By measuring the travel times of the pulses sent in both directions, determine the axial velocity of fluid passing through the path of the pulse. Repeated measurements are an average time to establish and minimize the random error. Sensors must be located as show the next figure:

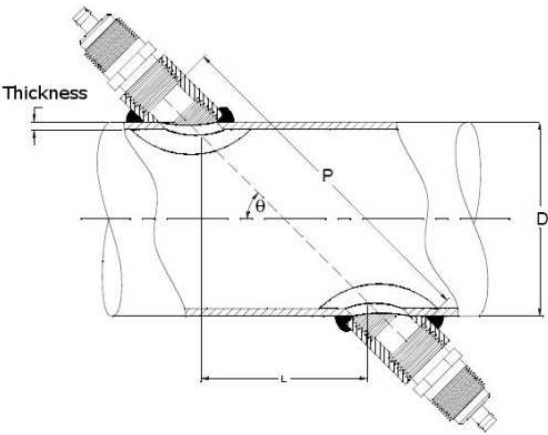


Fig. 9. Location of the sensors in the penstock.

Each sensor sends an ultrasonic signal and the delay time from downstream sensor (t_2) at upstream sensor (t_1) it's measured electronically. The sound propagation velocity of the moving fluid (c) is:

$$c = c_0 + \bar{v} \cos \theta \tag{9}$$

Were:

\bar{v} is water average velocity

Traveling time for propagating ultrasonic signals from downstream sensor to upstream sensor are:

$$t_1 = \frac{P}{c_0 - \bar{v} \cos \theta} \tag{10}$$

$$t_2 = \frac{P}{c_0 + \bar{v} \cos \theta} \tag{11}$$

Were:

P = distance between sensors (as can be seen on figure 9).

Therefore:

$$\frac{1}{t_1} - \frac{1}{t_2} = \frac{2\bar{v} \cos \theta}{P} = \frac{2\bar{v}L}{P} \quad (12)$$

Where:

L = inner signal distance between both sensor, parallel to penstock axe.

From last equation, velocity is obtained then:

$$\bar{v} = \frac{P^2 \Delta t}{2L t_1 t_2} \quad (13)$$

Where: $\Delta t = t_1 - t_2$

4.2 Instrumentation

For measurements were used two ultrasonic devices G.E. Panametrics, models PT868 and PT878, in different sections of the penstock, both in real time:

The characteristics of sensors are:

- Transducer clamp-on type (for external installation)
- Range: -12.2 to 12.2 m/s
- Accuracy (velocity): 0.5 to 1%
- Manufacturer: G.E. Panametrics
- The specifications assume a stable flow profile



Fig. 10. Electronic devices to perform Ultrasonic measurements.

4.3 Example

Some of the results obtained from ultrasonic measurements are presented in table 2 and figure 11 (Hernández 2010).

Test variables												
Power from electric generator [MW]	P_e	27.14	26.01	24.80	23.69	22.05	19.97	18.17	15.26	11.98	8.83	
Turbine inlet pressure [kPa]	p_{in}	3271.03	3276.53	3280.28	3284.06	3291.47	3299.50	3307.37	3320.12	3332.99	3342.57	
Flow measured by ultrasonic method [m³/s]	Q_u	9.56	9.16	8.82	8.48	7.96	7.32	6.77	5.86	4.84	3.89	
Calculated variables												
Water inlet velocity [m/s]	V_{in}	10.06	9.64	9.28	8.93	8.37	7.70	7.13	6.17	5.09	4.10	
Water outlet velocity [m/s]	V_{out}	1.56	1.50	1.44	1.39	1.30	1.20	1.11	0.96	0.79	0.64	
Test net head [m]	H_n	337.61	337.76	337.86	337.81	338.23	338.59	339.19	339.80	340.64	341.29	
Generator Efficiency [%]	η_g	98.45	98.44	98.43	98.41	98.40	98.35	98.26	97.97	97.50	96.85	
Mechanical power [kW]	P_m	27.57	26.42	25.20	24.07	22.41	20.31	18.49	15.58	12.28	9.12	
Turbine efficiency [%]	η_t	87.52	87.43	86.59	86.03	85.31	83.94	82.47	80.13	76.34	70.34	

Table 2. Variables obtained and calculated by ultrasonic method

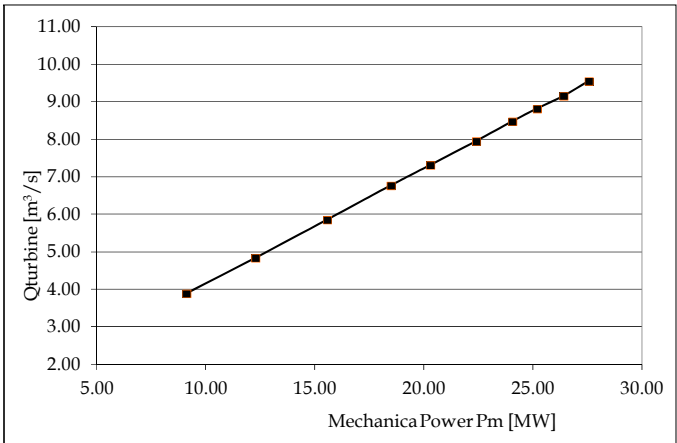


Fig. 11. Graphic of Flow vs Mechanical power, obtained by Ultrasonic method.

5. Comparison between methods

Present section showed a comparison between measurements obtained by ultrasonic and Gibson methods in one hydraulic turbine. The comparison was realized from tests in the same Power Plant with a short period of time between them. These comparisons were realized by Hernández (2010) in his Master Thesis, by measurements performed by Urquiza *et al* (2008).

In figure 12 can be observed a graphic of flow measured vs mechanical power, for both methods, which behavior is very similar.

Flow measured with ultrasonic and Gibson methods is very close and within the uncertainty of measurement at full load, however as measuring low flow, value of flow from ultrasonic method is less than the flow measured by Gibson, because the efficiencies vary strongly as the test powers are lower.

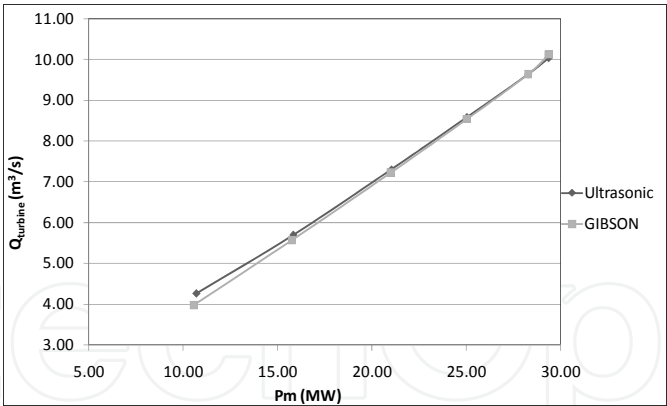


Fig. 12. Flow measured by both method vs Mechanical Power.

In figure 13 the behavior or the Net Head (H_n) are similar, however, are closer the values as they reach the maximum power (there are differences approximately 0.2 m between them) and virtually 0 to full load.

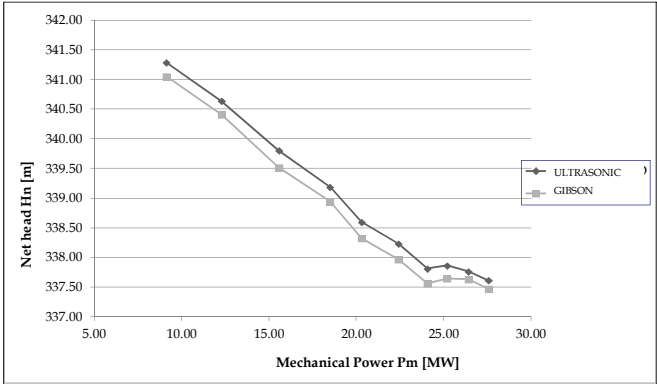


Fig. 13. Net head measured vs Mechanical Power.

The net head values for both methods (ultrasound and Gibson) are very similar and the same trends, but are more as they reach values close to maximum power as have differences of about 0.2 m and minimum loads almost 0 at full load.

Figure 14 shows a final comparison between the turbine efficiency vs. electrical power, here can be appreciated that measured efficiency by Gibson’s method is greater than ultrasound method, because the ultrasound method, due to it’s an experimental method, is follows that as water flow is lower or velocity is slower inside the penstock, inaccuracy is increasing, under which the results are less than the value obtained by Gibson, which is reliable and is supported by the IEC 41.

6. Other optical techniques for measurement of pressure applied on flow measurement

In CIICAp are developing pressure sensors based on optical methods to assist in measuring the flow through the above methods. The use of the sensors by optical means is an area of support for the electronic sensors, which is gaining strength. The type of arrangement may be from patterns interferometric on holographic tables until the micro actuator fully micro fabricated by surface micromachining on a single silicon wafer.

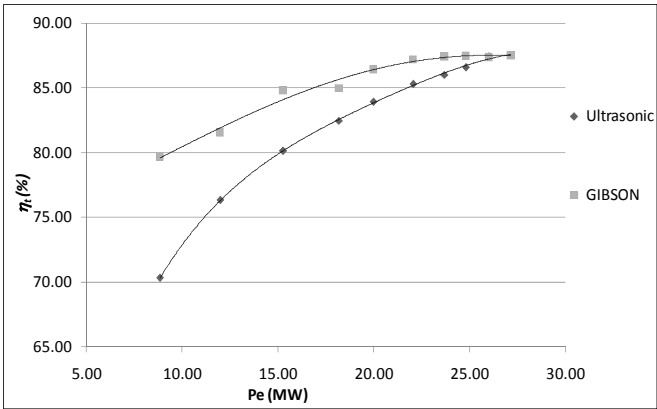


Fig. 14. Efficiency obtained by both methods vs Electric Power.

6.1 Fiber Bragg sensors

The use of Bragg gratings has different applications such as displacement, temperature and pressure sensors among others. A Bragg grating optical fiber can be defined as a periodic modulation (period or modulation of non-uniform) refractive index of the core of an optical fiber, usually single-mode, which can also be seen as a periodic arrangement of plates two films of different refractive indices designed to operate with a specific wavelength, an easier way to understand their function is imagining a beam of light (consisting of different wavelengths) travels within the fiber passing through Bragg grid (designed for a particular wavelength) will have two behaviors, such as a filter, it will only be rejected is that the wavelength at which it was designed, the second is as a mirror, in this case only reflect wavelength for which it was designed, other property that has the Bragg grating is that being in tension or compression, the grid changes its point of operation, this property is very useful for measuring the deformation of materials for pressure. Based on the response to tension or compression, the grid can be placed inside a chamber

Using fibers Bragg grating written in a novel high birefringence fiber by phase-mask method. The temperature and gas pressure characteristics of the fiber Bragg grating were analyzed and demonstrated quantitatively. Two Bragg wavelengths corresponding to the fast-axis mode and slow-axis mode shift linearly with temperature change and gas pressure change. Experimental results showed that this Hi-Bi fiber Bragg grating could be used to measure temperature and gas pressure simultaneously with a deviation of less than 1 °C and 0.5 MPa from the set values respectively (Guanghui *et al*, 2003).

Currently there are two configurations of Bragg grating. The most widely used are called-fiber Bragg gratings (FRB) (Hao-Jan *et al*, 2008 & Zhanxiong *et al*, 2008), which have been used in pressure sensors for low pressure range and high pressures equally. There exists application of hydrostatic pressure in resolutions up to 0.5% (Clarke 1995). Some variants of this type of fiber are long-period optical fibers gratings (Rao & Jackson 1996) and the chirped grating, also used in pressure sensors.

6.2 Multimode Interference

The multimode interference effect occurs when the diffracted light and in certain traveled distance can regroup [m]. The first application of this phenomenon was made in the design of bidirectional couplers on integrated optics (Niemeier & Ulrich, 1986). They have since

been developed a variety of optical devices based on this phenomenon in planar waveguides, such as Mach-Zehnder switches (Jenkins *et al*, 1994), couplers (Soldano *et al* 1991), ring lasers (van Roijen *et al*, 1994) and so on. An example of patterns Interferometric Mach-Zehnder Interferometer is, Can it be made using single-mode optical Fibers for the two arms as Shown in Figure 15.

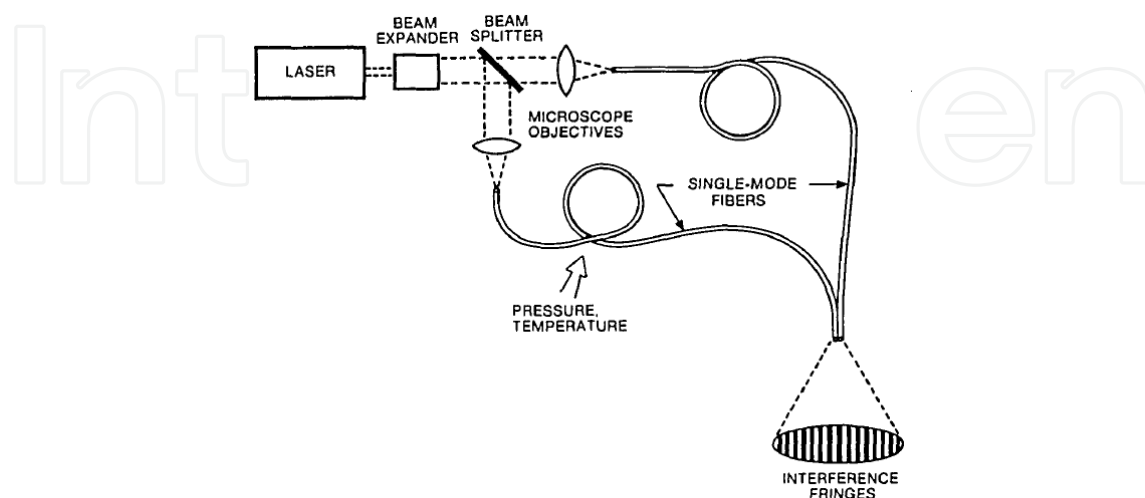


Fig. 15. Setup basic of Mach-Zehnder interferometer.

If the optical pathlengths of the two arms are nearly equal (to within the coherence length of the source), the light from the two fibers interferes to form a series of bright and dark fringes. A change in the relative phase of the light from one fiber with respect to the other is observed as a displacement of the fringe pattern.

Pressure sensitivity measurements were made with a 1.5-m length of one fiber in a cylinder, which could be pressurized to 345 kPa (50 psi) with nitrogen. Pressure measurements were made with a gauge reading to 345 Pa (0.05 psi). The fringe displacement was again recorded on video tape for repeated measurement.

Recently researches have presented studies on the interference between the guided modes in a multimode fiber, excited by a field from a single mode fiber. Under certain conditions, a reconstruction of the input field may be reproduced in amplitude and phase at specific distances within the multimode fiber, known as self-image distances. These conditions are determined by the physical parameters of the fibers used as the light source. If an optical fiber is spliced to the multimode fiber in the distance just self-image, the transmitted field will be sensitive to alterations of the physical parameters involved in the multimode fiber section. This can be used in pressure sensors, because the intensity of the output signal can be attenuated by altering the phase of modes propagated. The phase may be modified by changing the optical path length traveled by the guided modes or modifying the refractive index of the fiber coating.

Another technique consists of two MMI couplers, two arms and a membrane. One arm (arm 1) is located on the center of the membrane and the other arm (arm 2) is located on the edge. An input MMI coupler has been designed (as showed on figure 16) to divide input light into two equal-power lights in the two arms. When no pressure is applied to the membrane, the divided lights meet at the output MMI coupler in the same phase, so that

they can be constructively interfered at the output MMI coupler. When the pressure is applied to the membrane, the strain induced in the membrane due to deflection causes the phase changes in the two arms.

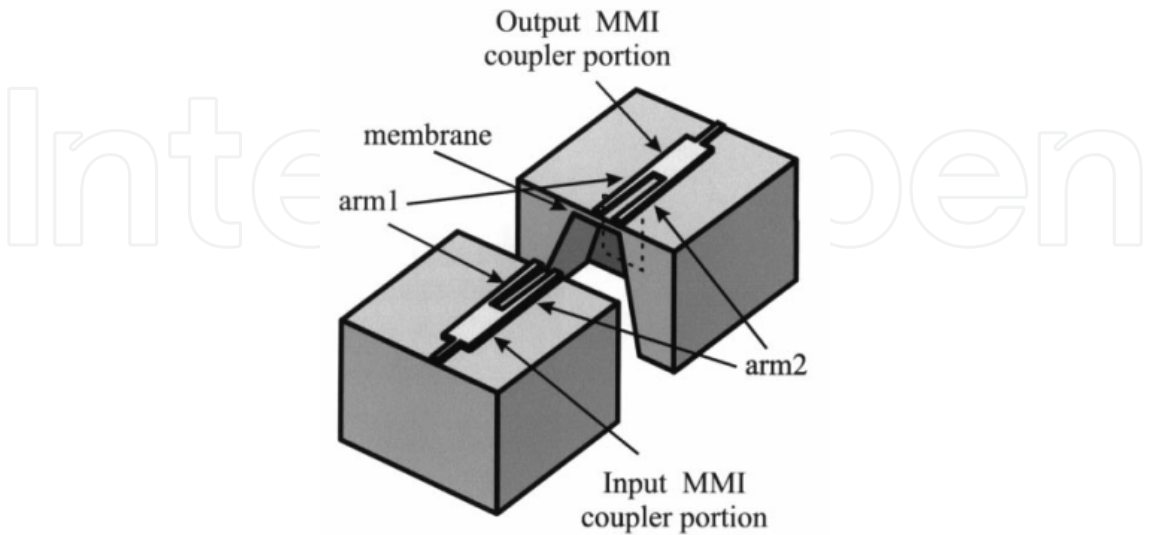


Fig. 16. Membrane with two couplers 1x2 and 2x1.

When no pressure is applied to the membrane Figure 17 (a), the divided lights meet at the output MMI coupler in the same phase, so that they can be constructively interfered at the output MMI coupler. When the pressure is applied to the membrane as can be observed on Figure 17(b), the strain induced in the membrane due to deflection causes the phase changes in the two arms by the following two mechanisms.

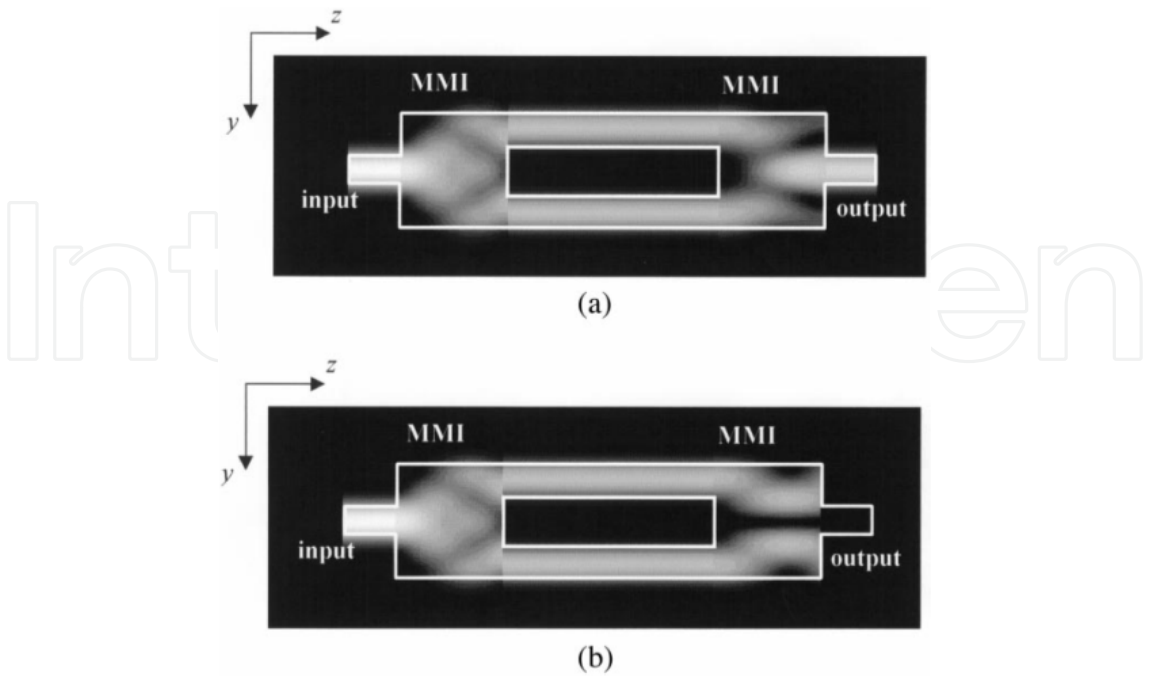


Fig. 17. Simulated light propagation through the MMI couplers in the proposed sensor when (a). no pressure is applied and (b) pressure is applied (not to scale).

This device has a size of 0.4 mm (width) x 13 mm (length) and the total thickness of the membrane is 7 μm . The device characteristics are measured using a He-Ne laser ($\lambda = 632.8 \text{ nm}$) as a light source. High sensitivity of 8.2 ppm/Pa has been obtained in the range of 100 kPa.

7. Conclusion

Was described the theoretical and practical aspects considered to carry out the measurement of flow by 3 selected methods: Gibson, Winter-Kennedy and Ultrasonic, as well as instrumentation selection and installation on hydroelectric power plants. Gibson's method is used by measuring the static pressure variation in two sections of pipe pressure for different loads of the turbine to determine the flow.

Finally, the results of Gibson's method were used for calibrated flow measuring Winter-Kennedy. This makes it possible to measure flow during normal operation of the turbine continuously.

In the section of the comparison between methods, was observed that for the ultrasonic method, as it decreases the load increases the inaccuracy of the method. Gibson's method applied is still more reliable and thus recommended in IEC standard.

Has been acquired experiences in the methods here described which help to analyze the performance of hydraulic turbines in Mexico and Poland.

In CIICAp are developing sensors based on optics fiber for measuring differential pressure, in addition to the obvious advantage of developing its own technology, can help in a future on flow measurement in hydroelectric power plants.

8. Acknowledgment

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